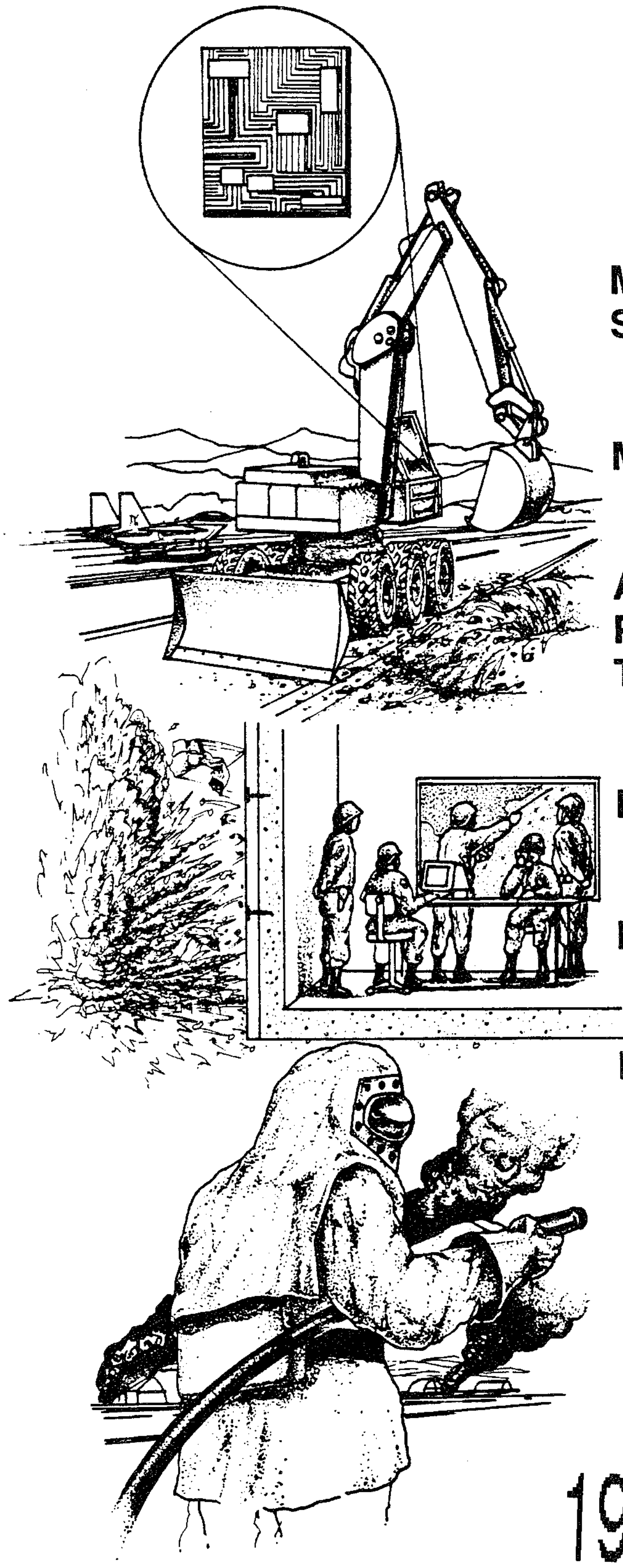

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MATERIALS FOR AIR-MOBILE STRUCTURES

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The objective of this research effort was to identify and catalog the engineering properties of commercially available, advanced composite materials with potential for use in lightweight shelter construction. A number of commercially available, potentially air-mobile, protective shelter construction materials were identified and divided into four main categories: Composites, Cores, Adhesives, and Ballistic Materials. The best materials in each category were described and a brief summary of each materials engineering properties was presented. The manufacturer of every material was identified.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this research effort was to identify and catalog the engineering properties of commercially available, advanced composite materials with potential for use in lightweight shelter construction.

B. BACKGROUND

Transportable shelters play an important role in the mission of the United States Air Force. Portable shelters are used for the expedient beddown of personnel during crises and mobility forces during deployment. They are also used as temporary structures in place of those vital air base facilities damaged by war or other disaster.

Current shelters are bulky, hard to erect and maintain, and provide only limited environmental protection. In addition, they provide little, if any, protection against small arms fire, much less the blast and fragmentation associated with indirect fire weapons and aerial munitions.

Based on the deficiencies of current shelters, the Air Force has expressed a need for an improved set of portable protective shelters.

C. SCOPE

It is hypothesized that the most promising approach to developing a new series of lightweight, air-mobile shelters involves coupling the use of modern aerospace composites with an innovative structural geometry. By designing structures in such a way as to exploit the strengths of current advanced composites, it may be possible to develop a family of lightweight shelters possessing significant structural hardness.

This report documents the materials survey phase of the improved air-mobile shelter design project. The scope of this phase was to identify and catalog the engineering properties of commercially available materials with potential for use in lightweight shelter construction. This shelter materials catalog was developed by searching existing literature. No laboratory testing was performed.

D. EVALUATION METHODOLOGY

Materials were selected based on their strength, weight and ballistic resistance. These properties were considered to be the most critical for air-mobile shelter design.

E. TEST DESCRIPTION

(N/A)

F. RESULTS

A number of commercially available, potentially air-mobile, protective shelter construction materials were identified and divided into four main categories: Composites, Cores, Adhesives, and Ballistic Materials. The best materials in each category were described, and a brief summary of each material's engineering properties was presented. The manufacturer of every material was identified.

G. CONCLUSIONS

Modern materials offer the opportunity to quickly improve present shelter designs, as well as develop new shelter concepts.

Better core and facing materials offer a quick improvement to current tactical shelter designs. In fact, future Army tactical shelters are being developed with composite materials in mind. The aluminum skins employed by current shelters will be replaced by graphite/epoxy panels. The graphite/epoxy skins will reduce shelter weight, improve ballistic protection, and increase electromagnetic shielding.

H. RECOMMENDATIONS

Future air-mobile shelter designs should exploit the impressive properties of modern engineering materials. The best shelter concepts will most likely involve a combination of materials, coupled with an innovative structural geometry. The geometry should exploit the strengths of each particular material.

PREFACE

This report was prepared by Applied Research Associates, Inc., P.O. Box 40128, Tyndall Air Force Base, FL 32403, under Scientific and Engineering Technical Assistance (SETA) contract F08635-88-C-0067 with the Air Force Civil Engineering Support Agency, Engineering Research Division (AFCESA/RAC), Tyndall Air Force Base, FL 32403. The work was performed between November 1989 and October 1991 as part of SETA Subtask 4.02, "Composite Materials for Structures".

Mr. Charles E. Bailey was the Air Force Project Monitor from November 1989 through August 1991. From September 1991 through its completion, the project was monitored by Mr. Walter C. Buchholtz.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

In response to TAF SON 314-88, the Engineering Research Division of the Air Force Civil Engineering Support Agency (HQ AFCESA/RAC) has initiated a multi-year research project to develop an improved set of air-mobile protective shelters.

B. BACKGROUND

Transportable shelters play an important role in the mission of the United States Air Force. Portable shelters are used for the expedient beddown of personnel during crises and mobility forces during deployment. They are also used as temporary structures in place of those vital air base facilities damaged by war or other disaster.

The Air Force utilizes three portable shelter deployment packages. They are referred to as Harvest Eagle, Harvest Bare, and Harvest Falcon. The Harvest Eagle soft wall shelters (i.e., tents) developed in 1957-65 and the Harvest Bare hard wall shelters developed in 1965-72 represent the mainstay capability of the Air Force to rapidly deploy and operate from forward locations. The Harvest Falcon bare base infrastructure centers on an enhanced version of a softwall shelter, the Tent Extendable Modular Personnel (TEMPER) tent. With the exception of the TEMPER tent, all existing transportable shelters utilize old technology. The current shelters are bulky, hard to erect and maintain, and provide only limited environmental protection. In addition, they provide little, if any, protection against small arms fire, much less the blast and fragmentation associated with indirect fire weapons and aerial munitions.

Based on the deficiencies of current shelters, the Air Force has expressed a need for an improved set of portable protective shelters. TAF SON 314-88, Statement of Operational Need for New Family of Portable Shelters, documents an immediate need for a family of air-mobile, easily erectable, maintainable, semi-hardened shelters.

C. SHELTER DESIGN

The design of any structure involves an interaction between structural analysis/design and materials selection/development. The design of protective shelters is considerably more complicated than that of a conventional structure.

Shelter design begins with the definition of the threat. The threat, or the attack which the shelter must withstand, is dependent on the mission of the structure being designed.

Once the threat has been specified, it must be translated into a series of free-field conventional weapon effects. Shelters may be subjected to a combination of airblast, fragmentation, penetration, ground shock, and cratering effects. Important weapon effects will depend on whether the structure will be aboveground or buried.

At this point in the design phase, it is necessary to specify the structural geometry and material properties. The geometry and material properties are used to calculate the structural properties (e.g., strength, stiffness, weight) of the key members.

Initial structural properties are used to construct a computer model of the shelter. The model is analyzed as it is being subjected to the appropriate weapon effect loadings. The stresses in and deflections of all key members are calculated. If the stresses and deflections of all members are within prescribed design limits, then the initial design is valid. This is usually not the case.

If the initial design is not satisfactory, there are two alternatives. The first alternative is to select/design new materials for the shelter. The second alternative is to change the geometry of the shelter. Member loadings can be changed dramatically by changing the configuration of the shelter.

A new structural model incorporating the revised combination of material properties and/or structural geometry is then analyzed. This process continues until a satisfactory structural response is calculated.

The shelter design process involves a combination of structural and materials engineering. If the design utilizes advanced composite materials, cooperation between structural and materials engineers becomes critical. Since most protective structures have been constructed of reinforced concrete, very few protective structural designers are familiar with the properties of aerospace composites. The materials engineer must therefore play a more active role in the design process of protective structures.

D. SCOPE OF REPORT

It is hypothesized that the most promising approach to developing a new series of lightweight, air-mobile shelters involves coupling the use of modern aerospace composites with an innovative structural geometry. By designing structures in such a way as to exploit the strengths of current advanced composites, it may be possible to develop a family of lightweight shelters possessing significant structural hardness.

This report documents the materials survey phase of the improved air-mobile shelter design project. The objective of this phase was to identify and catalog the engineering properties of commercially available, advanced composite materials with potential for use in lightweight shelter construction. This shelter materials catalog was developed by searching existing literature. No laboratory testing was performed.

SECTION II

LITERATURE REVIEW & TECHNICAL APPROACH

A. INTRODUCTION

A literature search of available information pertaining to composite materials and transportable shelters, was conducted through the Air Force Civil Engineering Support Agency's Technical Information Center (AFCESA/TIC).

A substantial number of recent books, reports, journals, and conferences dealing with composite materials exit, making it impossible to obtain and review all the references uncovered; therefore, a representative sample was selected for review. A list of the references requested is included in the Bibliography under the heading, "Properties and Mechanics of Advanced Composite Materials." These 23 references provide a realistic picture of the quantity and quality of information currently available on advanced composite structural materials. Some of the references focus on the engineering properties of composites, while others concentrate on the application of composites in design. Both types are useful to the design engineer. For the reader interested in searching additional references, the Engineers' Guide to Composite Materials [1] contains a bibliography of 78 reference books and 13 technical journals dealing with composite materials. Reference 1 also includes an excellent glossary of terms relating to composites.

Eight reports pertaining to transportable shelter research were also requested and reviewed. A list of these reports is given in the Bibliography under the heading, "Transportable Shelter Research." These references provide insight into recent Army and Air Force portable shelter research.

B. REVIEW OF SELECTED ADVANCED MATERIALS REFERENCES

Structural and mechanical engineers are beginning to routinely utilize advanced materials (e.g., composites, plastics, ceramics, adhesives, etc.) in their designs. The widespread application of these new materials in engineering design has created a need for accessible material property information. This need has resulted in the recent appearance of a multitude of engineering references pertaining to advanced, high-strength, lightweight materials. The remainder of this section is devoted to a brief review of several excellent reference books published since the mid-1980s.

In addition to an extensive discussion of the recreational, automotive, aerospace, marine, medical, electronic, and structural applications of composite materials, the Engineers' Guide to Composite Materials [1] contains more than 200 pages of property data for reinforcements, polymer matrix composites, metal matrix composites, and ceramic and glass matrix composites. As mentioned previously, this reference also contains an excellent bibliography and glossary of terms.

Another source of information on composite materials is a four-volume reference series, called the Handbook of Composites [2-5]. Volume 1: Strong Fibres [2] contains more than 700 pages of technical information pertaining to inorganic, carbon, and organic, high-modulus fibres. Volume 2: Structures and

Design [3] includes a survey of analysis techniques, design considerations, and design methods for fibrous composite structures. Volume 3: Failure Mechanics of Composites [4] describes the various failure mechanisms and the testing of composite materials. Volume 4: Fabrication of Composites [5] discusses the fabrication of composite materials, ranging from fiber-reinforced ceramics to biological composites.

The four-volume Engineered Materials Handbook [6-9] is another excellent materials reference series. Volume 1: Composites [6] contains more than 900 pages of information (161 articles) pertaining to properties, testing, analysis and design, manufacturing, failure analysis, and applications of advanced composite materials. Volume 2: Engineering Plastics [7] presents over 800 pages of similar information relevant to engineering plastics. Volume 3: Adhesives and Sealants [8] includes 97 articles comprising one of the most thorough reviews of the selection, design, properties, and uses of structural adhesives and sealants ever published. Volume 4: Ceramics and Glasses [9] contains 1100 pages of practical information on processing, properties, testing and characterization, design, and applications of various types of ceramics and glasses.

The most complete and concise set of engineering material property data for advanced, nonmetallic materials has been assembled by D.A.T.A., Inc. This reference series [10-12], called the "desk-top data bank," contains thousands of pages of material property information for composites, plastics, and adhesives. In addition, D.A.T.A. Inc.'s 2000-page reference on plastics is available as a computerized database [13].

The reference book, Composites & Laminates [10], is the broadest single source of data on engineering properties of modern composite materials. This reference contains data for over 3000 materials from more than 130 manufacturers. Up to 20 material properties are listed for each material. The 3000 materials are grouped into eight categories (Composites and Advanced Composites, Compounds, Films, Laminates, Panels, Prepregs, Profiles and Shapes, and Sheets), and ranked according to 12 material properties (Compressive Strength, Deflection Temperature at 264 psi, Density, Dielectric Strength, Elongation at Break, Flexural Modulus, Flexural Strength at Break, Izod Notched at RT, Linear Shrinkage, Tensile Modulus, Tensile Strength at Break, and Water Absorption).

The INTERNATIONAL PLASTICS SELECTOR [13] is the self-proclaimed "world's most extensive database of Plastics Materials." It is a computerized database of engineering information for over 12,700 plastic materials from more than 200 manufacturers. Plastics can be searched and sorted according to 50 physical, mechanical, electrical, thermal, and flammability properties. This database is updated quarterly to keep abreast of daily material changes. As an illustration of the rapid change occurring in the plastics industry, INTERNATIONAL PLASTICS SELECTOR sales literature states that, "1,613 new plastics materials were introduced, and 703 materials were discontinued between July 1989 and October 1989."

A subset of the engineering data contained in the INTERNATIONAL PLASTICS SELECTOR is contained in the reference, Plastics [11]. This reference lists physical, mechanical, thermal, and electrical properties for over 9000 commercially available plastics from more than 180 manufacturers. The 9000

plastics have been grouped into 61 generic categories (e.g., Acrylic, Epoxy, Nylon, Silicone, etc.), then ranked according to 22 material properties (Processing Temperature, Linear Mold Shrinkage, Melting Point, Density, Tensile Strength at Yield, Tensile Strength at Break, Percent Elongation at Break, Tensile Modulus, Flexural Strength at Yield, Flexural Modulus, Compressive Strength, Izod Notched at R.T., Hardness, Thermal Conductivity, Linear Thermal Expansion, Deflection Temperature at 264 psi, Deflection Temperature at 66 psi, Voltage Resistivity, Dielectric Strength, Dielectric Constant at 10^6 HZ, Dissipation Factor at 10^6 HZ, and Percent Water Absorption at 24 hours).

The reference book, Adhesives [12], concisely lists the physical, mechanical, and thermal properties of more than 3000 commercially available adhesives, sealants, and primers from more than 100 manufacturers. The adhesives are grouped into 12 classes, and ranked according to seven material properties (Flash Point, Glass Transition Temperature, Lap Shear Range - Low, Lap Shear Range - High, Service Temp Range - Low, Service Temp Range - High, and Viscosity).

C. PREVIOUS SHELTER MATERIAL SURVEYS

The concept of a catalog of engineering properties for potential shelter construction materials is not new.

In 1985, Mr. D. Robert Askins of the University of Dayton Research Institute suggested the creation of a shelter Materials Advisory Document (MAD) [14]. According to Mr. Askins, "The goal of this document will be to provide a focal point for gathering and disseminating information on materials available for use in the construction, repair, testing, and inspection of tactical shelters." Mr. Askins proposed a tentative list of shelter-related materials which should be included in the MAD. The list included: adhesives, cores, skins, fasteners, primers, paints, sealants, armor, gaskets, weather seals, potting compounds, core splice materials, repair materials, composites, foams, and metal hardware. He went on to give example data for typical adhesive and core materials.

In 1986, the Air Force Wright Aeronautical Laboratory published the results of a state-of-the-art survey of materials for developing a Transportable Collective Protection System (TCPS) [15]. This materials survey was conducted by Haug, Garic and Pharr, of Computer Sciences Corporation (CSC). Their approach was to solicit information directly from material manufacturers. They contacted more than 400 vendors of engineering materials. After analyzing all the information received, they grouped the materials into five categories: metals, plastics, composites, fabrics, and core materials. A fundamental assumption of the CSC survey was that engineering properties should be collected only for "finished" materials readily available from current manufacturers. Therefore, information on additive compounds, resins, fillers, and reinforcements was not included in the survey, since they are not structural materials or finished products in and of themselves.

Reference 15 concluded with opinions regarding the most appropriate combination of materials for shelter construction. In summary, Haug, Garic and Pharr felt that no single, homogeneous material inherently possesses the performance characteristics required to serve effectively in the TCPS applica-

tion. A satisfactory material could be achieved by combining various optimum materials from suitable material categories into a composite, a multilayered fabric, or a laminate. Laminated materials constructed from various combinations of the top-rated metals, plastics, and fabrics, together with the top-rated core material will likely provide the optimum overall properties.

D. GATHERING MATERIAL PROPERTY DATA

1. Following a Lead

Since Mr. Askins' proposed MAD [14] was very similar in objective to this project, the authors telephoned Mr. Askins to determine the current status of the MAD. Mr. Askins stated that the MAD project had been discontinued before it ever really started. The members of the tactical shelter design community could not decide which properties, of what materials, should be included in the MAD. Since the scope of the MAD was never properly defined, the effort was discontinued.

2. A Lesson Learned

The materials survey conducted by Haug, Garic, and Pharr [15] illustrates the difficulty in soliciting materials information directly from manufacturers. Despite contacting more than 400 manufacturers, their efforts resulted in "complete" engineering data for only 81 materials: 13 metals, 31 plastics, 12 composites, 17 fabrics, and 8 cores.

3. Technical Approach

Engineering properties of materials can be obtained from many sources, including: reference books, technical journals and reports, conference proceedings, computerized databases, and manufacturers' literature.

Technical journals, reports, and conference proceedings are most useful for obtaining detailed information about a particular material. They are not, however, an appropriate source for gathering information pertaining to an entire class of materials. Attempting to extract a broad range of engineering data from these sources would take a prohibitive amount of time.

Reference 15 illustrates the difficulty of obtaining information directly from material manufacturers.

To gather as much information as possible, in a limited time, the information-gathering process should begin with reference books (e.g., References 1-12) and computerized databases (e.g., Reference 13). Once a solid core of information has been gathered from these sources, it can be supplemented with data obtained from technical reports and manufacturers' literature.

SECTION III

MATERIALS FOR AIR-MOBILE STRUCTURES

A. INTRODUCTION

The two most important shelter design constraints are shelter size, and the combined dead and live loads which must be supported (i.e., resisted). The dead loads consist of the self-weight of the structure, plus the weight of any ballistic armor or insitu covering material (e.g., soil or rock rubble). The live loads are loads imposed on the structure due to conventional weapon attack. Airblast, fragmentation, ground shock, and ballistic impact are the primary live loads which must be resisted. Air-mobile shelters are subject to an additional design constraint, air-transportability. Weight and packing volume limitations are the main restrictions imposed by this constraint. Due to their high strength and low weight, modern composite materials are an obvious choice for air-mobile shelter construction. Many advanced composites have strength-to-weight ratios several times greater than those of the best metals. Figure 1 [16] is a plot of specific tensile strength (strength/density) versus specific tensile modulus (modulus/density) for several commercially available, unidirectional composites and for steel and aluminum. The composite strengths and moduli were calculated from fiber properties, using the "rule of mixtures."

Knowing the tensile strength (or modulus) of the reinforcing fibers and the matrix material, the tensile strength (or modulus) of a unidirectional composite in the fiber direction can be estimated using the rule of mixtures. According to the rule of mixtures, the composite tensile strength is estimated as

$$T_c = T_f V_f + T_m V_m \tag{1}$$

where, T_f is the tensile strength of the fibers, V_f is the fiber volume fraction, T_m is the tensile strength of the matrix material, V_m is the matrix volume fraction, and T_c is the tensile strength of the composite. To estimate composite moduli in the fiber direction, the rule of mixtures is expressed as

$$E_c = E_f V_f + E_m V_m \tag{2}$$

where, E_f, E_m, and E_c are the fiber, matrix, and composite moduli, respectively.

By varying the type and volume fraction of fibers, composite fabricators can produce unidirectional composites with a wide range of tensile strengths and stiffnesses. Thousands of composite materials are commercially available. These materials are used in applications ranging from sporting goods (e.g., tennis rackets, golf clubs, skis, etc.) to space vehicles. The goal of this study was to determine which of these commercially available materials have the greatest potential for air-mobile shelter construction.

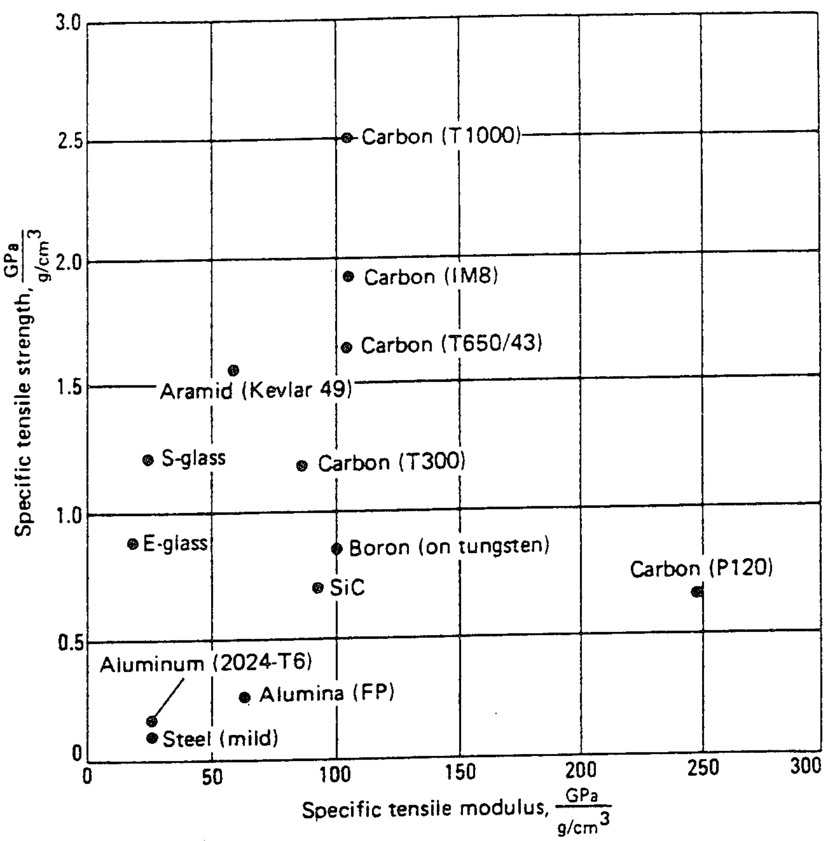

Figure 1. Specific Tensile Strength versus Specific Tensile Modulus for Various Commercially Available 65 Vol% Unidirectional Epoxy-Matrix Composites and for Steel and Aluminum. Note that T1000 Carbon Fiber is Available only in Limited Quantities [16].

Based on current tactical shelter research and available composites literature, several materials have been identified as candidates for air-mobile shelter construction. The materials have been grouped into four main categories: Composites, Cores, Adhesives, and Ballistic Materials. The best materials in each of these categories are described in the following sections.

B. COMPOSITES

Due to its breadth of coverage (over 3000 materials) and concise format (materials ranked by mechanical properties), Composites & Laminates [10] provides an excellent source for preliminary composite material selection. The ranked property data in Reference 10 were used to identify several composites as possible air-mobile shelter construction materials. The materials were selected based on their tensile, compressive, and flexural strengths.

Shear strength was not used as a material selection criterion. The

shear strengths of all unidirectional polymer-matrix composites are relatively small, and do not vary greatly from each other. Even the strongest unidirectional polymer-matrix composites have shear strengths of 20 ksi or less.

Although modulus is an important structural analysis parameter, it was not used as a material selection criterion. A composite material with a large modulus is not necessarily a good shelter construction material. Unidirectional polymer-matrix composites, loaded in the fiber direction, exhibit linear stress-strain response up to the point of tensile failure. Thus, for two materials having the same ultimate tensile strength, the strain at failure is inversely proportional to tensile modulus. If strain-energy at failure is defined as the area under the stress-strain curve up to the point of failure, the stiffer material also has a smaller strain-energy at failure.

Ideally, shelter construction materials should have high strength and large strain at failure (and consequently, a high strain-energy at failure). Such materials will be able to withstand larger live-load-induced displacements, dissipate more energy, and result in more survivable shelters.

Following the material definitions in reference 10, the candidate air-mobile shelter composite materials have been divided into six subcategories: Advanced Composites, Compounds, Laminates, Panels and Sheets, Prepregs, and Profiles and Shapes. The differences between classes are often quite subtle.

1. Advanced Composites

A composite is a macroscopically homogeneous material created by the synthetic assembly of two or more materials (a selected filler or reinforcing elements, and a compatible matrix binder) to obtain specific characteristics and properties [1]. Advanced composites are strong, tough materials created by combining one or more stiff, high-strength reinforcing fibers with a compatible resin system [1]. Advanced composites can be substituted for metals in many structural applications.

Table 1 lists the strongest materials in the Advanced Composites category, based on tensile, compressive, and flexural strength. Only those materials which ranked in the top three in at least one of the three strength categories, are listed.

TABLE 1. STRONGEST ADVANCED COMPOSITES [10].

	Strength (ksi)		
Material	Tension	Compression	Flexure
Thornel 2500	470	250	-
Cycom 1010	273	215	231
NY-30GF	225	-	-
EMI Shielding Gr LS AC 40-60	-	-	154
NY-40GF	-	216	-
EMI Shielding Gr AC 30-60	-	-	93

A brief description and summary of material properties for each of the six strongest advanced composite materials is given in Table A-1. (See Appendix A - Material Properties of Selected Composites.)

All the material strength data presented in this report were obtained from static loading conditions. Engineering reference books and manufacturers' literature do not usually contain data for dynamic loading; they rarely, if ever, contain data relevant to the exceptionally high strain rates typical of weapon loadings. However, since the goal of this report is simply to gather enough material property data to be able to screen materials for air-mobile structure construction, static data should suffice. In addition, some evidence suggests that composite material properties are not greatly affected by strain rate. After extensive dynamic testing of shelter core materials, Kuhbander and Caldwell [17] concluded that, "there is relatively little effect on honeycomb core shear strength due to test speed." Based on impact testing of composite panels, Krinke, Barber, and Nicholas [18] observed that, "A general trend of bending strength increasing with strain rate exists for most of the data but the magnitude appears small." In any case, once candidate structural materials are identified, strain rate issues can be addressed, and dynamic testing can be performed.

2. Compounds

Compounds are the intimate admixture of a polymer with other ingredients, such as fillers, softeners, plasticizers, reinforcement, catalysts, pigments, or dyes [6]. A thermoset compound usually contains all the ingredients necessary for the finished product, while a thermoplastic compound may require addition of pigments, blowing agents, and so forth.

Compounds come in a wide range of forms to meet specific processing requirements. The two most popular compounds are Bulk Molding Compound (BMC) and Sheet Molding Compound (SMC).

Bulk Molding Compound is a thermosetting resin, mixed with stranded reinforcement, fillers, etc., in the form of a viscous compound suitable for use in injection or compression molding [1].

Sheet Molding Compound is a composite of glass fibers, polyester resins, and pigments, fillers, and other additives, which have been compounded and processed into sheet form to facilitate handling in the molding operation [1].

Table 2 lists the strongest materials in the Compounds category, based on tensile, compressive, and flexural strength. As before, only those materials which ranked in the top three in at least one of the three strength categories are listed.

TABLE 2. STRONGEST COMPOUNDS [10].

Material	Strength (ksi) Tension	Compression	Flexure
E 261H	35	42	85
RTP 287 TFE 10	33	-	-
E 21718 x 61	32	44	58
E 260H	-	42	68

A brief description and summary of material properties for each of the four strongest compounds are given in Table A-2.

Table 3 lists the strongest materials in the Bulk Molding Compounds category, based on tensile, compressive, and flexural strength. The materials listed in Table 3 are not the highest ranking according to reference 10. The top BMCs listed in Reference 10 are a family of materials manufactured by Premix, Inc., designated Premi-Glas. The listed strengths were so large, however, that they were judged to be incorrect. Reference 19, Engineering Plastics & Composites, verified that the values were, indeed, incorrect.

TABLE 3. STRONGEST BULK MOLDING COMPOUNDS [10].

Material	Strength (ksi) Tension	Compression	Flexure
Polytron E-106	14	-	28
Polystruc M-106	14	28	28
Polycor C-106	14	30	28
Silryn S-106	-	29	-

A brief description and summary of material properties for each of the four strongest BMCs are given in Table A-3.

Table 4 lists the strongest materials in the Sheet Molding Compounds category, based on tensile, compressive, and flexural strength. As with the BMCs, the SMCs listed in Table 4 are not the highest ranking according to reference 10. The top SMCs listed in Reference 10 are all Premi-Glas materials. As before, the Premi-Glas data are known to be erroneous [19].

TABLE 4. STRONGEST SHEET MOLDING COMPOUNDS [10].

Material	Strength (ksi) Tension	Compression	Flexure
Lytex 4105	140	-	185
8057	75	-	-
8068	62	-	103
VE 49595	-	42	-
Polytron E-206	-	32	-
Silryn S-206	-	32	-
Flomat 5580	-	-	112

A brief description and summary of material properties for each of the seven strongest SMCs are given in Table A-4.

3. Laminates

A laminate is a sheet of material made of several different bonded layers [10]. One or more of the bonded layers is itself often a composite.

Table 5 lists the strongest materials in the Laminates category, based on tensile, compressive, and flexural strength.

TABLE 5. STRONGEST LAMINATES [10].

Material	Strength (ksi) Tension	Compression	Flexure
Cycom 985-1 GT-2148	240	200	250
Cycom 985-1 GF 6135H5	120	-	-
Gillfab 1086	110	-	-
Cycom 1827 GT 6150	-	225	310
Cycom 3100 + T300	-	167	242

A brief description and summary of material properties for each of the five strongest Laminates are given in Table A-5.

4. Panels & Sheets

Panels and Sheets are flat formed, finished products, similar in construction to composites [10].

Table 6 lists the strongest materials in the Panels category, based on tensile, compressive, and flexural strength. Note that only one material had a listed compressive strength.

TABLE 6. STRONGEST PANELS [10].

Material	Tension	Strength (ksi) Compression	Flexure
Tred-Safe	32	-	39
Fire Snuf 25A 1230	15	-	-
Fire Snuf 25A 820	15	-	-
Dion FR 6131	-	26	29
Filon Standard	-	-	28

A brief description and summary of material properties for each of the five strongest Panels are given in Table A-6.

Table 7 lists the strongest materials in the Sheets category, based on tensile, compressive, and flexural strength. Reference 10 lists Extren 625 as the sheet material with the greatest compressive strength. However, these data are known to be erroneous [20], and as a result, Extren 625 is omitted from Table 7.

TABLE 7. STRONGEST SHEETS [10].

Material	Tension	Strength (ksi) Compression	Flexure
Lamitex G215	60	70	55
Ryertex G-10	55	-	-
Ryertex G-11	50	-	-
Lamitex Grade G-5	-	70	-
Lamitex Grade G-9	-	70	55
Lamitex T6G91	-	-	63

A brief description and summary of material properties for each of the six strongest Sheets are given in Table A-7.

5. Prepregs

A Prepreg (preimpregnated material) is a partially processed combination of a resin and a reinforcing material, which can be used to make a composite [10].

Table 8 lists the strongest materials in the Prepregs category, based on tensile, compressive, and flexural strength.

A brief description and summary of material properties for each of the eight strongest Prepregs are given in Table A-8.

TABLE 8. STRONGEST PREPREGS [10].

Material	Strength (ksi) Tension	Compression	Flexure
Hexcel F584/T5A190	445	-	-
Hexcel F584/T5A145	414	-	-
Hexcel F584/T4A145	404	-	-
AVCO 5505/4 - BORON	-	425	297
AVCO 5521/4 - BORON	-	425	-
Hexcel F584/T8A145	-	278	-
FX 91C34	-	-	310
Fortafil 3(C)	-	-	300

6. Profiles & Shapes

Profiles and Shapes are finished products [10]. They are not necessarily reinforced, and are often molded.

Table 9 lists the strongest materials in the Profiles and Shapes category, based on tensile, compressive, and flexural strength.

TABLE 9. STRONGEST PROFILES AND SHAPES [10].

Material	Strength (ksi) Tension	Compression	Flexure
Bridon SM	214	-	-
N-S Pultruded Composites	200	-	-
Pultruded Bar Stock	110	-	-
Vespel SP-22 "S"	-	475	-
Polypenco Ultem 1000	-	420	-
Vespel SP-1 "S"	-	350	-
Vespel SP-21 "S"	-	350	-
HYR	-	-	120
ETR-FR-C-P	-	-	100
HST-II-P	-	-	100

A brief description and summary of material properties for each of the ten strongest Panels and Sheets are given in Table A-9.

C. CORES

Current Air Force, air-transportable, tactical shelters are made with wall, floor, and roof panels of sandwich construction [17]. These sandwich panels typically consist of aluminum faces, adhesively bonded to a resin-impregnated, paper honeycomb core. Floor panels requiring high impact resistance often employ end-grain balsa wood as a core material.

Sandwich construction is common in nature. The human skull is a prime example of natural sandwich construction. The skull consists of a cellular core, laminated between solid inner and outer shells [21]. This geometry maximizes strength and stiffness, while minimizing weight.

Lightweight fillers are routinely laminated between strong facing sheets to produce strong, stiff, lightweight structural panels. Balsa wood and rigid structural foams are frequently employed as sandwich core materials. Reference 21 contains an entire chapter (Chapter 9: "The Design of Sandwich Panels with Foam Cores") devoted to the optimum design of foam-filled sandwich panels, subject to strength, stiffness, and weight constraints.

The highest strength-to-weight and stiffness-to-weight ratio sandwich panels constructed to date have utilized honeycomb cores. Honeycomb [22] is a product consisting of very thin sheets attached in such a manner as to form connecting cells. It closely resembles the honeycomb made by bees. Honeycomb can be manufactured from virtually any thin-sheet material. Common metallic-core materials are aluminum, corrosion-resistant steel, titanium, and nickel-based alloys. The most common nonmetallic core materials are Nomex, fiberglass, and kraft paper. Non-metallic core is normally dipped in liquid phenolic, polyester, or polyimide resin to achieve the final density. Honeycomb has been produced from over 500 different materials, the most recent being graphite, aramid, and ceramic [22].

Standard hexagonal honeycomb, shown schematically in Figure 2, is the most common cellular honeycomb configuration [23].

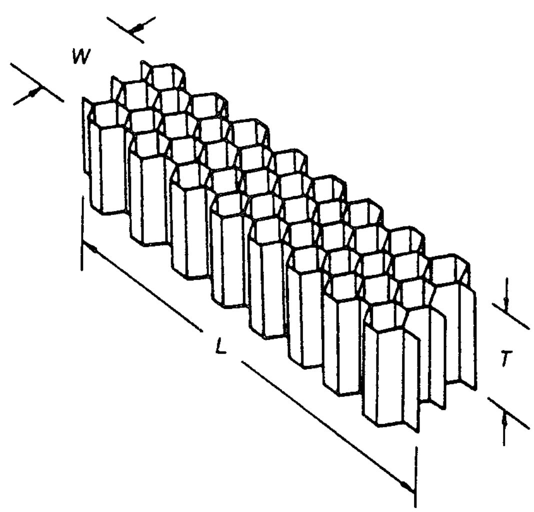

Figure 2. Hexagonal Honeycomb Geometry

As a result of the method of fabrication, hexagonal cell honeycomb is strongly orthotropic. The mechanical properties used to quantify honeycomb response are: bare compression strength, stabilized compression strength and modulus,

"L" and "W" direction (see Figure 2) shear strengths and moduli, and crush strength. In general, bare compression strength is roughly 90 percent of the stabilized strength, and crush strength is 50 percent of the stabilized strength [22]. The "L" direction shear strength and modulus values are approximately twice those in the "W" direction. Figures 3-7 present typical hexagonal honeycomb properties, as a function of density, for a variety of materials. Figure 3 shows the stabilized compressive strength of Nomex, Fiberglass, 5052 Aluminum, and 5056 Aluminum honeycomb as a function of density. Figures 4 and 5 show typical "L" and "W" direction honeycomb shear strengths as a function of density. Figures 6 and 7 show typical "L" and "W" direction honeycomb shear moduli as a function of density.

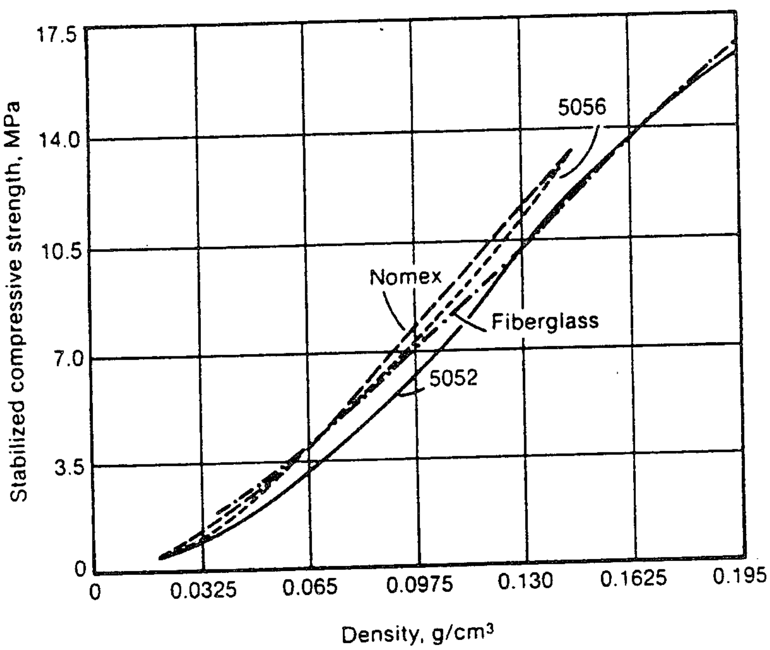

Figure 3. Typical Honeycomb Stabilized Compression Strength vs. Density [22,23].

The basic premise behind sandwich design is that the facings carry the in-plane loads, and the core carries the shear loads. Reference 24, <u>The Basics of Bonded Sandwich Construction</u>, offers specific guidance for designing honeycomb sandwich members. The data in Figures 4-7 indicate that grade 2024 hexagonal aluminum honeycomb offers the greatest shear resistance for a given density. Since the main purpose of the sandwich core is to carry shear loads, aluminum honeycomb appears to be the core material of choice. This conclusion is confirmed by reference 25, which states, "aluminum honeycomb is a structural core material which, when bonded between high strength faces, produces a sandwich panel that has the highest strength-to-weight ratio of any structural material".

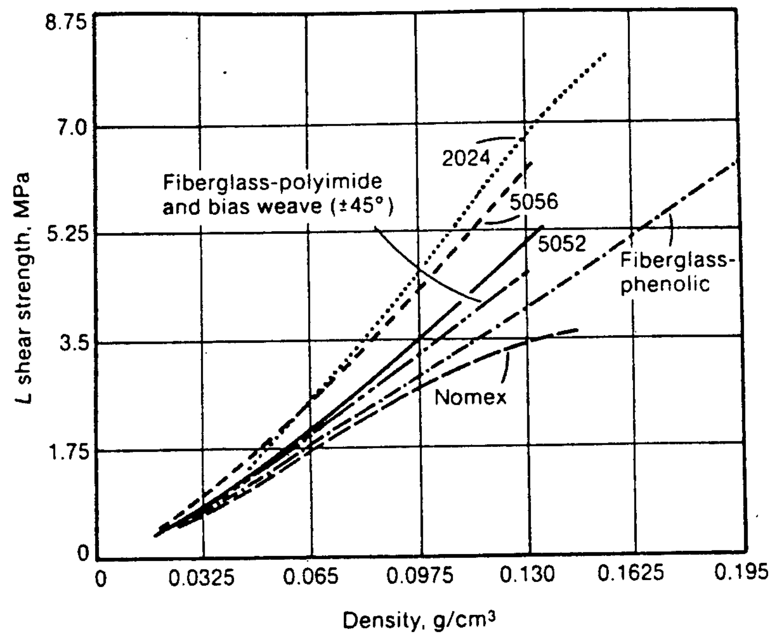

Figure 4. Typical Honeycomb "L" Shear Strength vs. Density [22,23].

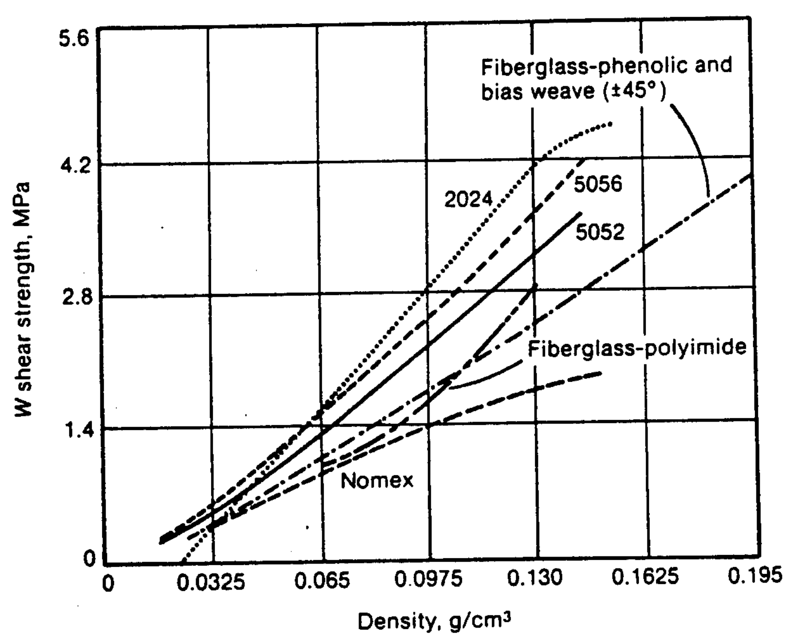

Figure 5. Typical Honeycomb "W" Shear Strength vs. Density [22,23].

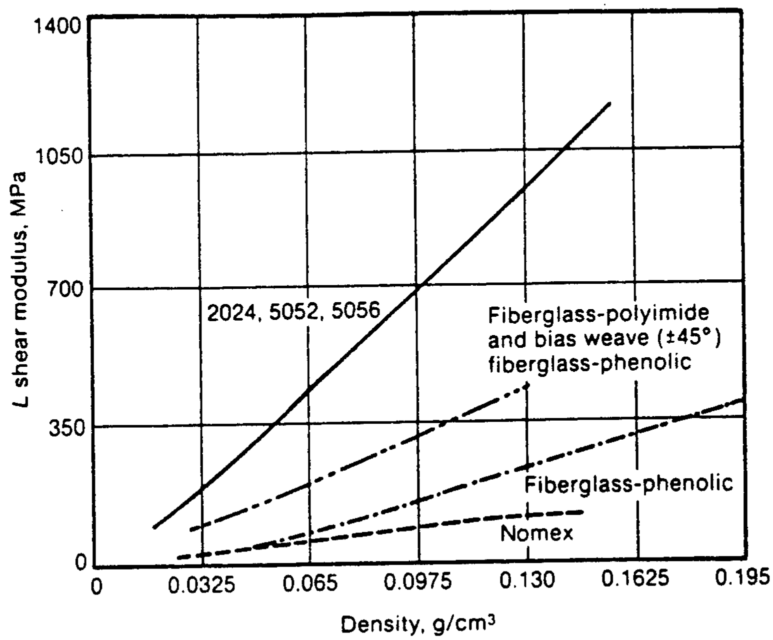

Figure 6. Typical Honeycomb "L" Shear Modulus vs. Density [22,23].

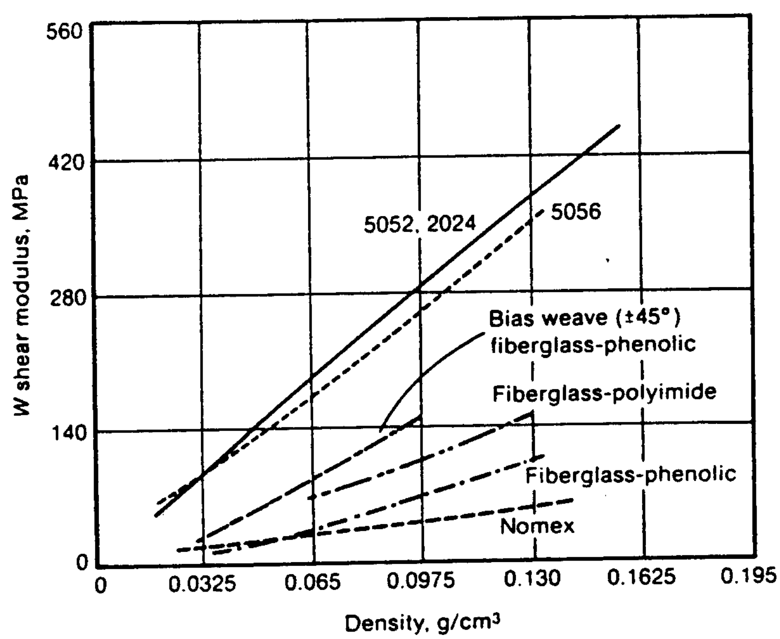

Figure 7. Typical Honeycomb "W" Shear Modulus vs. Density [22,23].

If future air-mobile shelter concepts utilize sandwich construction, Military Grade hexagonal aluminum honeycomb is recommended as a core material. Hexcel and American Cyanamid are two producers of Military Grade aluminum honeycomb (Hexcel refers to their product as "Specification Grade"). Quantitative mechanical properties of several densities of aluminum honeycomb are given in references 23 and 25. Typical properties for Hexcel, Specification Grade 2024 hexagonal aluminum honeycomb, are given in Appendix B.

D. ADHESIVES

There are 12 main family groups of adhesives. These 12 main groups are divided into a multitude of subgroups containing innumerable individual formulations. Reference 12 lists over 3000 commercially available adhesives. The large number of available adhesives often makes the selection process quite difficult. However, when ultimate adhesive performance is required, adhesive selection is much simpler. Lees [26] recommends that toughened epoxies be used whenever maximum performance is demanded from either a mechanical or structural assembly. They possess excellent strength, impact resistance, and durability. Toughened epoxies currently offer the best adhesive performance.

Several factors must be considered when selecting adhesives for shelter construction. Obvious considerations are the loads and the environmental conditions to which the adhesive will be subjected. The adhesive must also be chemically compatible with the substrate materials. In addition, the adhesive cure conditions must be compatible with the materials being bonded.

Shelter components will be fabricated in a factory. Shelter erection will obviously be performed in the field. Since autoclaves will not be available in the field, field bonding applications will require different adhesives than those used in the factory.

1. Factory Bonding

Toughened epoxy film adhesives are recommended for factory fabrication. Film adhesives are extensively used in the aircraft industry. Film adhesives are easy to handle and place, and the toughened epoxy films are among the strongest adhesives available. However, since film adhesives require cold storage, as well as elevated temperature and pressure cure conditions, they are not appropriate for field use.

Two candidate adhesives for factory bonding are Metlbond 1137-1, manufactured by Narmco Materials, and FM 73, by American Cyanamid. Both are toughened epoxy film adhesives; are compatible with metal and composite substrates; and require an elevated temperature and pressure cure cycle (typically 1 hour at 250 degrees F and 40 psi). In the 0.030 psf weight, Metlbond 1137-1 has a lap shear strength of 7500 psi [12], and FM 73 has a lap shear strength of 6200 psi [27]. American Cyanamid [27] recommends FM 73 adhesive for use with its Cycom advanced composite materials. Recall (see Table 1) that Cycom 1010 is one of the strongest available composites.

2. Field Bonding

Since elevated temperature and pressure curing are not possible in the field, a two-part epoxy adhesive with room temperature cure is recommended for field construction. The first component is the epoxy, and the second component is the hardener. Two-part systems do not require refrigeration, and the separate components have an indefinite storage life [12]. After curing at room temperature, they are rigid and tough.

Scotch-Weld 2216 B/A, manufactured by the 3M Company, is a candidate adhesive for field construction. This two-part epoxy adhesive is compatible with metal, wood, plastic, and stone substrates. After curing for 7 days at 77 degrees F, it develops a lap shear strength of 4900 psi [12].

E. BALLISTIC MATERIALS

Selecting materials for ballistic protection is not simple. To date, no direct correlation between a material's physical or mechanical properties (including impact strength), and its potential for ballistic protection, has been determined [15]. In addition, materials are not usually subjected to ballistic testing, unless they are being expressly evaluated for a particular ballistic protective capability.

There are three primary materials currently used in lightweight ballistic applications. They are S-2 Glass fibers, manufactured by Owens-Corning; Kevlar fibers, by Dupont; and Spectra fibers, by Allied Fibers. For ballistic protection applications, the fibers are woven into a tight mesh or fabric. One layer of fabric provides virtually no ballistic protection. Numerous layers must be stacked in order to develop significant ballistic resistance. Typical applications require between 10 and 50 layers [28].

Fabrics can be used for both hard and soft armor applications. In soft armor, the layers stand on their own, acting as the sole source of ballistic protection. In hard armor applications, the fabric layers are embedded in a thermoplastic, phenolic, or epoxy matrix. In general, soft armor performs better (weighs less) for low-level threats, while hard armor is better for more severe threats [28].

A lightweight hard armor study was recently conducted by Frank, et. al. at Battelle Memorial Institute [28]. The ballistic threat for this study was a 7.62-mm, full metal-jacketed bullet, with a nominal mass of 9.7 grams (150 grains), impacting at a velocity of 2750 ft/sec. The results of the study are shown in Table 10. Note that all the materials are competitively priced for the same level of protection. However, Spectra fiber clearly has the weight advantage, being lower by a factor of two. It would appear that Spectra is the best material for this threat.

TABLE 10. COMPARISON OF BALLISTIC FIBERS FOR HARD ARMOR [28].

Fiber	Aerial Density (lb/ft^2)	Aerial Cost ($\$/ft^2$)
Spectra	4.5	202.50
Kevlar 49	9.0	180 - 360
S-2 Glass	9.5	237.50

A similar lightweight armor study was conducted by Bless, et. al. at the University of Dayton Research Institute [29]. The threat for this study was a 60-grain, fragment-simulating projectile (FSP). It was found that Spectra, Kevlar, and S-2 Glass reinforced plastics can all defeat the 60-grain FSP at the threat velocity. However, only the Spectra-reinforced plastic can withstand the threat, while still meeting the weight constraint of 2 psf.

Based on the results of the lightweight armor studies described in references 28 and 29, it appears that Spectra fiber-reinforced plastic currently offers the greatest ballistic protection at the minimum weight.

The fact that the United States Army has recently developed a new lightweight helmet constructed of Spectra-900 fiber [30] is further conformation of Spectra's superior ballistic performance.

SECTION IV

SUMMARY AND CONCLUSIONS

A. SUMMARY

A number of commercially available, potential air-mobile, protective shelter construction materials have been identified and divided into four main categories: Composites, Cores, Adhesives, and Ballistic Materials. The best materials in each category are described herein, and a brief summary of each material's engineering properties presented. The manufacturer of every material is identified.

B. CONCLUSIONS

Modern materials offer the opportunity to quickly improve present shelter designs, as well as develop new shelter concepts.

1. Present Shelters

Present air-mobile tactical shelters are typically constructed from sandwich panels, consisting of 1-mm thick aluminum skins bonded to a 2-inch thick, resin-impregnated, paper honeycomb core. These shelters provide very little protection from weapon effects or small arms fire. Small arms protection must be provided by covering the shelter with a ballistic resistant material.

Better core and facing materials offer a quick improvement to current tactical shelter designs. In fact, future Army tactical shelters are being developed with composite materials in mind [30]. The aluminum skins employed by current shelters will be replaced by graphite/epoxy panels. The graphite/epoxy skins will reduce shelter weight, improve ballistic protection, and increase electromagnetic shielding [30].

It is unclear from Reference 30 whether the core material will be improved as well. Using aluminum honeycomb, in combination with graphite/epoxy faces, would result in sandwich panels having significant strength and stiffness. In addition, the aluminum honeycomb core would further increase the shielding properties of the panels. Reference 23 recommends aluminum honeycomb as an RF shielding material.

2. Future Designs

Future air-mobile shelter designs should exploit the impressive properties of modern engineering materials. The best shelter concepts will most likely involve a combination of materials, coupled with an innovative structural geometry. The geometry should exploit the strengths of each particular material.

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APPENDIX A

MATERIAL PROPERTIES OF SELECTED COMPOSITES

TABLE A-1. ADVANCED COMPOSITES - MATERIAL PROPERTIES [10].

Material: **Thornel 2500**
Manufacturer: Amoco Performance
Description: Fiber reinforced TS (thermosetting) epoxy
Tensile Strength, psi: 4.70×10^5
Tensile Modulus, psi: 2.50×10^6
Compressive Strength, psi: 2.50×10^5
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: -----

Material: **Cycom 1010**
Manufacturer: American Cyanamid
Description: Glass fiber reinforced TS epoxy
Tensile Strength, psi: 2.73×10^5
Tensile Modulus, psi: 1.90×10^7
Compressive Strength, psi: 2.15×10^5
Flexural Strength, psi: 2.31×10^5
Flexural Modulus, psi: 1.85×10^7
Density, lbs/ft^3: 97.4

Material: **NY-30GF**
Manufacturer: Compound Tech Inc
Description: Glass fiber reinforced TP (thermoplastic) Polyamide-Nylon 6
Tensile Strength, psi: 2.25×10^5
Tensile Modulus, psi: 1.30×10^6
Compressive Strength, psi: 2.25×10^4
Flexural Strength, psi: 3.30×10^4
Flexural Modulus, psi: 1.10×10^6
Density, lbs/ft^3: 86.2

Material: **EMI Shielding Gr LS AC 40-60**
Manufacturer: Phillips Petroleum
Description: Carbon fiber reinforced TP Polyphenylene Sulfide
Tensile Strength, psi: 1.52×10^5
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.54×10^5
Flexural Modulus, psi: 1.41×10^7
Density, lbs/ft^3: -----

Material: **NY-40GF**
Manufacturer: Compound Tech Inc
Description: Glass fiber reinforced TP Polyamide-Nylon 6
Tensile Strength, psi: 2.50×10^4
Tensile Modulus, psi: 2.10×10^6
Compressive Strength, psi: 2.16×10^5
Flexural Strength, psi: 3.50×10^4
Flexural Modulus, psi: 1.40×10^6
Density, lbs/ft^3: 91.1

TABLE A-1. ADVANCED COMPOSITES - MATERIAL PROPERTIES [10].
(Continued)

Material: **EMI Shielding Gr AC 30-60**
Manufacturer: Phillips Petroleum
Description: Carbon fiber fabric reinforced TP
Polyphenylene Sulfide
Tensile Strength, psi: 7.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 9.30×10^4
Flexural Modulus, psi: 6.80×10^6
Density, lbs/ft^3: -----

TABLE A-2. COMPOUNDS - MATERIAL PROPERTIES [10].

Material: **E 261H**
Manufacturer: Fiberite
Description: Long glass fiber reinforced TS epoxy
Tensile Strength, psi: 3.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 4.20×10^4
Flexural Strength, psi: 8.50×10^4
Flexural Modulus, psi: 4.20×10^6
Density, lbs/ft^3: 118

Material: **RTP 287 TFE 10**
Manufacturer: RTP Company
Description: Carbon fiber reinforced TP Polyamide-Nylon 6/6
Tensile Strength, psi: 3.30×10^4
Tensile Modulus, psi: 4.20×10^6
Compressive Strength, psi: 2.40×10^4
Flexural Strength, psi: 5.10×10^4
Flexural Modulus, psi: 3.10×10^6
Density, lbs/ft^3: 86.8

Material: **E 21718 x 61**
Manufacturer: Fiberite
Description: Carbon fiber reinforced TS epoxy Tensile strength, psi: 3.20×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 4.40×10^4
Flexural Strength, psi: 5.80×10^4
Flexural Modulus, psi: 8.20×10^6
Density, lbs/ft^3: 94.3
Material: **E 260H**
Manufacturer: Fiberite
Description: Long glass fiber reinforced TS epoxy
Tensile Strength, psi: 2.70×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 4.20×10^4
Flexural Strength, psi: 6.80×10^4
Flexural Modulus, psi: 4.10×10^6
Density, lbs/ft^3: 118

TABLE A-3. BULK MOLDING COMPOUNDS - MATERIAL PROPERTIES [10].

Material: **Polytron E-106**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced unspecified/proprietary binder
Tensile Strength, psi: 1.40×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 2.80×10^4
Flexural Strength, psi: 2.80×10^4
Flexural Modulus, psi: 1.70×10^6
Density, lbs/ft^3: 109

Material: **Polystruc M-106**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced unspecified/proprietary binder
Tensile Strength, psi: 1.40×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 2.80×10^4
Flexural Strength, psi: 2.80×10^4
Flexural Modulus, psi: 1.80×10^6
Density, lbs/ft^3: 111

Material: **Polycor C-106**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced TS Vinyl Ester
Tensile Strength, psi: 1.40×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 3.00×10^4
Flexural Strength, psi: 2.80×10^4
Flexural Modulus, psi: 1.80×10^6
Density, lbs/ft^3: 112

Material: **Silryn S-106**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced TS Polyester
Tensile Strength, psi: 1.35×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 2.90×10^4
Flexural Strength, psi: 2.80×10^4
Flexural Modulus, psi: 1.70×10^6
Density, lbs/ft^3: 112

TABLE A-4. SHEET MOLDING COMPOUNDS - MATERIAL PROPERTIES [10].

Material: **Lytex 4105**
Manufacturer: Quantum Composites
Description: Glass fiber reinforced TS epoxy
Tensile Strength, psi: 1.40×10^5
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.85×10^5
Flexural Modulus, psi: 6.00×10^6
Density, lbs/ft^3: 119

Material: **8057**
Manufacturer: Applied Composites
Description: Graphite fiber reinforced TS polyester
Tensile Strength, psi: 7.50×10^4
Tensile Modulus, psi: 1.25×10^7
Compressive Strength, psi: 2.99×10^4
Flexural Strength, psi: 9.60×10^4
Flexural Modulus, psi: 8.00×10^6
Density, lbs/ft^3: 105

Material: **8068**
Manufacturer: Applied Composites
Description: Graphite fiber reinforced TS polyester
Tensile Strength, psi: 6.20×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.03×10^5
Flexural Modulus, psi: 5.00×10^6
Density, lbs/ft^3: 114

Material: **VE 49595**
Manufacturer: Fiberite
Description: Glass fiber reinforced TS Vinyl Ester
Tensile Strength, psi: 3.90×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 4.20×10^4
Flexural Strength, psi: 7.00×10^4
Flexural Modulus, psi: 2.80×10^6
Density, lbs/ft^3: 117

Material: **Silryn S-206**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced TS Polyester
Tensile Strength, psi: 1.60×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 3.20×10^4
Flexural Strength, psi: 3.20×10^4
Flexural Modulus, psi: 1.90×10^6
Density, lbs/ft^3: 109

TABLE A-4. SHEET MOLDING COMPOUNDS - MATERIAL PROPERTIES [10].
(Continued)

Material: **Polytron E-206**
Manufacturer: Polymer Engineering
Description: Glass fiber reinforced unspecified/proprietary binder
Tensile Strength, psi: 1.60×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 3.20×10^4
Flexural Strength, psi: 3.10×10^4
Flexural Modulus, psi: 1.90×10^6
Density, lbs/ft^3: 107

Material: **Flomat 5580**
Manufacturer: Freeman Chemicals
Description: Glass fiber reinforced TS Polyester Tensile
Strength, psi: 1.00×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.12×10^5
Flexural Modulus, psi: 1.60×10^6
Density, lbs/ft^3: 114

TABLE A-5. LAMINATES - MATERIAL PROPERTIES [10].

Material: **Cycom 985-1 GT-2148**
Manufacturer: American Cyanamid
Description: Graphite fiber reinforced TS epoxy
Tensile Strength, psi: 2.40×10^5
Tensile Modulus, psi: 1.95×10^7
Compressive Strength, psi: 2.00×10^5
Flexural Strength, psi: 2.50×10^5
Flexural Modulus, psi: 1.75×10^7
Shear Strength, psi: 1.70×10^4
Density, lbs/ft^3: 97.4

Material: **Cycom 985-1 GF 6135H5**
Manufacturer: American Cyanamid
Description: Glass fiber reinforced TS epoxy
Tensile Strength, psi: 1.20×10^5
Tensile Modulus, psi: 1.05×10^7
Compressive Strength, psi: 1.15×10^5
Flexural Strength, psi: 1.65×10^5
Flexural Modulus, psi: 1.00×10^7
Shear Strength, psi: 1.00×10^4
Density, lbs/ft^3: 101

Material: **Gillfab 1086**
Manufacturer: MC Gill Corp
Description: Graphite fiber reinforced TS epoxy
Tensile Strength, psi: 1.10×10^5
Tensile Modulus, psi: 1.18×10^7
Compressive Strength, psi: 1.10×10^5
Flexural Strength, psi: 1.57×10^5
Flexural Modulus, psi: 1.29×10^7
Shear Strength, psi: -----
Density, lbs/ft^3: 98.6

Material: **Cycom 1827 GT 6150**
Manufacturer: American Cyanamid
Description: Graphite fiber reinforced TS epoxy
Tensile Strength, psi: -----
Tensile Modulus, psi: -----
Compressive Strength, psi: 2.25×10^5
Flexural Strength, psi: 3.10×10^5
Flexural Modulus, psi: 1.83×10^7
Shear Strength, psi: 1.79×10^4
Density, lbs/ft^3: 98.0

TABLE A-5. LAMINATES - MATERIAL PROPERTIES [10].
(Continued)

Material: **Cycom 3100 + T300**
Manufacturer: American Cyanamid
Description: Graphite fiber reinforced TS Bismaleimide
Tensile Strength, psi: 2.70×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 1.67×10^5
Flexural Strength, psi: 2.42×10^5
Flexural Modulus, psi: -----
Shear Strength, psi: 1.93×10^4
Density, lbs/ft^3: -----

TABLE A-6. PANELS - MATERIAL PROPERTIES [10].

Material: **Tred-Safe**
Manufacturer: Resolite
Description: Glass fiber reinforced TP Polyester/Acrylic
Tensile Strength, psi: 3.20×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 3.90×10^4
Flexural Modulus, psi: 1.17×10^6
Density, lbs/ft^3: -----

Material: **Fire Snuf 25A 1230**
Manufacturer: Resolite
Description: Glass fiber reinforced TP Acrylic
Tensile Strength, psi: 1.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.90×10^4
Flexural Modulus, psi: 7.00×10^5
Density, lbs/ft^3: -----

Material: **Fire Snuf 25A 820**
Manufacturer: Resolite
Description: Glass fiber reinforced TP Acrylic
Tensile Strength, psi: 1.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.90×10^4
Flexural Modulus, psi: 7.00×10^5
Density, lbs/ft^3: -----

Material: **Dion FR 6131**
Manufacturer: Koppers Co, Inc
Description: Glass fiber reinforced TS Polyester
Tensile Strength, psi: 1.38×10^4
Tensile Modulus, psi: 4.50×10^5
Compressive Strength, psi: 2.69×10^4
Flexural Strength, psi: 2.94×10^4
Flexural Modulus, psi: 1.00×10^6
Density, lbs/ft^3: -----

Material: **Filon Standard**
Manufacturer: Filon
Description: Glass fiber reinforced TP Polyester/Acrylic
Tensile Strength, psi: 1.09×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 2.82×10^4
Flexural Modulus, psi: 1.10×10^6
Density, lbs/ft^3: -----

TABLE A-7. SHEETS - MATERIAL PROPERTIES [10].

Material: **Lamitex G215**
Manufacturer: Franklin Fibre
Description: Glass fiber reinforced TS epoxy
Tensile Strength, psi: 6.00×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 7.00×10^4
Flexural Strength, psi: 5.50×10^4
Flexural Modulus, psi: 2.50×10^6
Density, lbs/ft^3: 109

Material: **Ryertex G-10**
Manufacturer: Ryerson
Description: Glass fabric reinforced TS epoxy
Tensile Strength, psi: 5.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 6.50×10^4
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: -----

Material: **Ryertex G-11**
Manufacturer: Ryerson
Description: Glass fabric reinforced TS epoxy
Tensile Strength, psi: 5.00×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 6.00×10^4
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: -----

Material: **Lamitex Grade G-5**
Manufacturer: Franklin Fibre
Description: Glass fabric reinforced TS Melamine
Tensile Strength, psi: 3.70×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 7.00×10^4
Flexural Strength, psi: 4.40×10^4
Flexural Modulus, psi: 1.70×10^6
Density, lbs/ft^3: 119

Material: **Lamitex Grade G-9**
Manufacturer: Franklin Fibre
Description: Glass fabric reinforced TS Melamine
Tensile Strength, psi: 3.70×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 7.00×10^4
Flexural Strength, psi: 5.50×10^4
Flexural Modulus, psi: 2.50×10^6
Density, lbs/ft^3: 119

TABLE A-7. SHEETS - MATERIAL PROPERTIES [10].
(Continued)

Material: **Lamitex T6G91**
Manufacturer: Franklin Fibre
Description: Glass fabric reinforced TS Polyimide
Tensile Strength, psi: -----
Tensile Modulus, psi: -----
Compressive Strength, psi: 5.80×10^4
Flexural Strength, psi: 6.35×10^4
Flexural Modulus, psi: 5.00×10^6
Density, lbs/ft^3: 119

TABLE A-8. PREPREGS - MATERIAL PROPERTIES [10].

Material: **Hexcel F584/T5A190**
Manufacturer: Hexcel
Description: Carbon Tape reinforced TS epoxy
Tensile Strength, psi: 4.45×10^5
Tensile Modulus, psi: 2.68×10^7
Compressive Strength, psi: 2.74×10^5
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: -----

Material: **Hexcel F584/T5A145**
Manufacturer: Hexcel
Description: Carbon Tape reinforced TS epoxy
Tensile Strength, psi: 4.14×10^5
Tensile Modulus, psi: 2.59×10^7
Compressive Strength, psi: 2.51×10^5
Flexural Strength, psi: 2.65×10^5
Flexural Modulus, psi: 2.24×10^7
Density, lbs/ft^3: -----

Material: **Hexcel F584/T4A145**
Manufacturer: Hexcel
Description: Carbon Tape reinforced TS epoxy
Tensile Strength, psi: 4.04×10^5
Tensile Modulus, psi: 2.19×10^7
Compressive Strength, psi: 2.69×10^5
Flexural Strength, psi: 2.85×10^5
Flexural Modulus, psi: 2.05×10^7
Density, lbs/ft^3: -----

Material: **AVCO 5505/4 - BORON**
Manufacturer: Avco Specialty
Description: Boron Filament reinforced TS epoxy
Tensile Strength, psi: 2.46×10^5
Tensile Modulus, psi: 3.04×10^7
Compressive Strength, psi: 4.25×10^5
Flexural Strength, psi: 2.97×10^5
Flexural Modulus, psi: 2.75×10^7
Density, lbs/ft^3: 125

Material: **AVCO 5521/4 - BORON**
Manufacturer: Avco Specialty
Description: Boron Filament reinforced TS epoxy
Tensile Strength, psi: 2.20×10^5
Tensile Modulus, psi: 3.04×10^7
Compressive Strength, psi: 4.25×10^5
Flexural Strength, psi: 2.59×10^5
Flexural Modulus, psi: 2.75×10^7
Density, lbs/ft^3: 125

TABLE A-8. PREPREGS - MATERIAL PROPERTIES [10].
(Continued)

Material: **Hexcel F584/T8A145**
Manufacturer: Hexcel
Description: Carbon Tape reinforced TS epoxy
Tensile Strength, psi: 3.41×10^5
Tensile Modulus, psi: 1.96×10^7
Compressive Strength, psi: 2.78×10^5
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: -----

Material: **FX 91C34**
Manufacturer: Fiberite
Description: Glass Fiber reinforced TS epoxy
Tensile Strength, psi: 1.90×10^5
Tensile Modulus, psi: 7.80×10^6
Compressive Strength, psi: -----
Flexural Strength, psi: 3.10×10^5
Flexural Modulus, psi: 9.00×10^6
Density, lbs/ft^3: 127

Material: **Fortafil 3(C)**
Manufacturer: Fortafil Fibers
Description: Carbon Fiber reinforced TS epoxy
Tensile Strength, psi: 2.64×10^5
Tensile Modulus, psi: 1.90×10^7
Compressive Strength, psi: -----
Flexural Strength, psi: 3.00×10^5
Flexural Modulus, psi: 1.80×10^7
Density, lbs/ft^3: -----

TABLE A-9. PROFILES AND SHAPES - MATERIAL PROPERTIES [10].

Material: **Bridon SM**
Manufacturer: Bridon Composites
Description: Glass fiber reinforced TS polyester Tensile Strength, psi: 2.14×10^5
Tensile Modulus, psi: 6.96×10^6
Compressive Strength, psi: -----
Flexural Strength, psi: 2.61×10^5
Flexural Modulus, psi: 6.63×10^6
Density, lbs/ft^3: 125

Material: **N-S Pultruded Composites**
Manufacturer: National-Standard
Description: E-Glass, S2 Glass & Kevlar fiber reinforced unspecified/proprietary matrix
Tensile Strength, psi: 2.00×10^5
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: -----
Flexural Modulus, psi: -----
Density, lbs/ft^3: 124

Material: **Pultruded Bar Stock**
Manufacturer: Polygon Company
Description: Glass fiber reinforced unspecified/proprietary matrix
Tensile Strength, psi: 1.10×10^5
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: -----
Flexural Modulus, psi: 5.50×10^6
Density, lbs/ft^3: 124

Material: **Vespel SP-22 "S"**
Manufacturer: EI DuPont
Description: Graphite reinforced TS polyimide
Tensile Strength, psi: 7.50×10^3
Tensile Modulus, psi: -----
Compressive Strength, psi: 4.75×10^5
Flexural Strength, psi: 1.40×10^4
Flexural Modulus, psi: 7.00×10^5
Density, lbs/ft^3: 103

Material: **Polypenco Ultem 1000**
Manufacturer: The Polymer Corp
Description: TP polyetherimide
Tensile Strength, psi: -----
Tensile Modulus, psi: 4.30×10^5
Compressive Strength, psi: 4.20×10^5
Flexural Strength, psi: 2.10×10^4
Flexural Modulus, psi: 4.80×10^5
Density, lbs/ft^3: 79.3

TABLE A-8. PROFILES AND SHAPES - MATERIAL PROPERTIES [10].
(Continued)

Material: **Vespel SP-1 "S"**
Manufacturer: EI DuPont
Description: TS polyimide
Tensile Strength, psi: 1.25×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: 3.50×10^5
Flexural Strength, psi: 1.90×10^4
Flexural Modulus, psi: 4.50×10^5
Density, lbs/ft^3: 89.3

Material: **Vespel SP-21 "S"**
Manufacturer: EI DuPont
Description: Graphite Fiber reinforced TS polyimide
Tensile Strength, psi: 9.50×10^3
Tensile Modulus, psi: -----
Compressive Strength, psi: 3.50×10^5
Flexural Strength, psi: 1.60×10^4
Flexural Modulus, psi: 5.50×10^5
Density, lbs/ft^3: 94.3

Material: **HYR**
Manufacturer: Haysite Plastics
Description: Unspecified/proprietary
Tensile Strength, psi: 1.00×10^5
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.20×10^5
Flexural Modulus, psi: -----
Density, lbs/ft^3: 117

Material: **ETR-FR-C-P**
Manufacturer: Haysite Plastics
Description: Unspecified/proprietary
Tensile Strength, psi: 3.50×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.00×10^5
Flexural Modulus, psi: -----
Density, lbs/ft^3: 114

Material: **HST-II-P**
Manufacturer: Haysite Plastics
Description: Unspecified/proprietary
Tensile Strength, psi: 4.00×10^4
Tensile Modulus, psi: -----
Compressive Strength, psi: -----
Flexural Strength, psi: 1.00×10^5
Flexural Modulus, psi: -----
Density, lbs/ft^3: 117

APPENDIX B

PROPERTIES OF HEXAGONAL 2024 ALUMINUM HONEYCOMB

TABLE B-1. PROPERTIES OF HEXAGONAL 2024 ALUMINUM HONEYCOMB [23].

Material: **1/8-2024-0.0015**
Manufacturer: Hexcel
Density, lbs/ft^3: 5.0
Stabilized Compressive Strength, psi: 840
Stabilized Compressive Modulus, ksi: 200
Crush Strength, psi: 425
"L" Direction Shear Strength, psi: 500
"L" Direction Shear Modulus, ksi: 82.0
"W" Direction Shear Strength, psi: 315
"W" Direction Shear Modulus, ksi: 33.0

Material: **1/8-2024-0.002**
Manufacturer: Hexcel
Density, lbs/ft^3: 6.7
Stabilized Compressive Strength, psi: 1330
Stabilized Compressive Modulus, ksi: 300
Crush Strength, psi: 640
"L" Direction Shear Strength, psi: 760
"L" Direction Shear Modulus, ksi: 118
"W" Direction Shear Strength, psi: 470
"W" Direction Shear Modulus, ksi: 45.0

Material: **1/8-2024-0.0025**
Manufacturer: Hexcel
Density, lbs/ft^3: 8.0
Stabilized Compressive Strength, psi: 1900
Stabilized Compressive Modulus, ksi: 380
Crush Strength, psi: 840
"L" Direction Shear Strength, psi: 960
"L" Direction Shear Modulus, ksi: 148
"W" Direction Shear Strength, psi: 590
"W" Direction Shear Modulus, ksi: 54.0

Material: **1/8-2024-0.003**
Manufacturer: Hexcel
Density, lbs/ft^3: 9.5
Stabilized Compressive Strength, psi: 2500
Stabilized Compressive Modulus, ksi: 480
Crush Strength, psi: 1120
"L" Direction Shear Strength, psi: 1150
"L" Direction Shear Modulus, ksi: 170
"W" Direction Shear Strength, psi: 650
"W" Direction Shear Modulus, ksi: 64.0

TABLE B-1. PROPERTIES OF HEXAGONAL 2024 ALUMINUM HONEYCOMB [23].
(Continued)

Material: **3/16-2024-0.0015**
Manufacturer: Hexcel
Density, lbs/ft^3: 3.5
Stabilized Compressive Strength, psi: 500
Stabilized Compressive Modulus, ksi: 86
Crush Strength, psi: 200
"L" Direction Shear Strength, psi: 290
"L" Direction Shear Modulus, ksi: 55.0
"W" Direction Shear Strength, psi: 180
"W" Direction Shear Modulus, ksi: 23.0

Material: **1/4-2024-0.0015**
Manufacturer: Hexcel
Density, lbs/ft^3: 2.8
Stabilized Compressive Strength, psi: 320
Stabilized Compressive Modulus, ksi: 40
Crush Strength, psi: 110
"L" Direction Shear Strength, psi: 200
"L" Direction Shear Modulus, ksi: 42.0
"W" Direction Shear Strength, psi: 120
"W" Direction Shear Modulus, ksi: 19.0

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